Application of Uncertainty and Variability in LCA

Part I: A General Framework for the Analysis of Uncertainty and Variability in Life Cycle Assessment (*Int. J. LCA 5/1998*)
Part II: Dealing with Parameter Uncertainty and Uncertainty due to Choices in Life Cycle Assessment (*Int. J. LCA 6/1998*)

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Part II: Dealing with Parameter Uncertainty and Uncertainty due to Choices in Life Cycle Assessment

Abstract

Results of product assessments are often criticised as to their handling of uncertainty. Therefore, it is necessary to develop a comprehensive methodology reflecting parameter uncertainty in combination with uncertainty due to choices in the outcome of LCAs. This paper operationalises the effect of combined parameter uncertainties in the inventory and in the characterisation factors for global warming and acidification for the comparison of two exemplary types of roof gutters. For this purpose, Latin Hypercube sampling is used in the matrix (inventory) method. To illustrate the influence of choices, the effect on LCA outcomes is shown of two different allocation procedures in open-loop recycling and three time horizons for global warming potentials. Furthermore, an uncertainty importance analysis is performed to show which parameter uncertainties mainly contribute to uncertainties in the comparison and the separate environmental profiles of the product systems. These results can be used to prioritise further data research.

Keywords: Allocation rules, parameter uncertainty, LCA; Latin hypercube simulation, parameter uncertainty, LCA; LCA, parameter uncertainty; Life Cycle Assessment, parameter uncertainty; open-loop recycling, parameter uncertainty, LCA; parameter uncertainty, LCA; probabalistic simulation, parameter uncertainty, LCA; scenario analysis, parameter uncertainty, LCA; simulation, Latin hypercube simulation, parameter uncertainty, LCA; simulation, probabalistic simulation, parameter uncertainty, LCA; uncertainty, LCA; variability, parameter

1 Introduction

The ultimate goal of environmental life cycle assessments (LCAs) is to provide information for decisions which will lead to environmental improvement of economies. However, LCAs may give rise to incorrect decisions when uncertainty and variability are not properly taken into account. Although at present model uncertainties due to the lack of spatial variability and temporal variability in the assessment generally cannot be made operational in LCA case studies, other types of uncertainty, such as parameter uncertainty and uncertainty due to choices, potentially can (HUIJBREGTS, 1998).

To illustrate parameter uncertainty and uncertainty due to choices, this paper compares two types of roof gutters with respect to their potential contribution to the environmental categories global warming (time horizon 20, 100 and 500 years) and acidification, using simplified inventory data. Using probabilistic modelling and scenario analysis, it shows the influence on LCA model outcomes of parameter uncertainties, of the choice of different allocation rules applied to open-loop recycling processes, and of different time horizons for global warming potentials. Furthermore, it couples the uncertainty analysis with an uncertainty importance analysis, which verifies the parameters that introduce the largest uncertainty in model outcomes. Finally, it discusses the feasibility of the application of this methodology in "real-life" LCAs and possibilities for simplifying the analysis. These studies may help in developing a comprehensive methodology for the inclusion of parameter uncertainty and uncertainty due to choices in LCA studies.

2 Data Input

2.1 Inventory

The matrix method, developed by HEIJUNGS (1994, 1996), is used to perform the inventory analysis. The inventory table I is computed with the following formula (HEIJUNGS, 1996):

$$I = H \times G^{-1} \times u \quad (1)$$

where:

I = Inventory table;
H = Environmental intervention matrix;
G = Technology matrix;
u = External supply vector, related to the functional unit.

An important advantage of the matrix method over other inventory methods is that the method easily deals with self-referring groups of processes (HEIJUNGS, 1994). The matrix method has already been used for extensive life cycle inventories, such as the inventories for energy systems (FRISCHKNECHT et al., 1996).

The functional unit used in the comparison of roof gutters A1 and A2 is "the discharge of rain water falling on the roof of a one-family building during fifty years". The application of 10 m of roof gutter fulfils this function for about 25 years. It is expected that part of both types of roof gutters will be recycled in the product system "Sewage pipes". The cut-off method and the avoided-impacts method are used to allocate the environmental burdens associated with the recycling of the products. These methods reflect two extreme visions on how to allocate environmental burdens in open-loop recycling processes and both were judged defensible by experts (KORTMAN et al., 1996). The cut-off method allocates the environmental interventions caused by the waste recycling process to the receiving product system S, while the avoided-impacts method allocates the environmental interventions caused by the waste recycling process to the product system Ax, but also credits system Ax by substracting the avoided environmental interventions from the original inventory table of Ax. The inventory data of the two roof gutter systems are given in **Tables 1** through 3.

Parameter uncertainty in the inventory analysis of the two product systems is characterised with the help of "Uncertainty factors (UFs)" which are given in the **Tables 3 and 4.** UFs are used to represent inventory data uncertainties as a triangular uncertainty distribution. The minimum and maximum values[1] of parameter P_x are assumed to be:

$$P_{x,\min} = \frac{P_{x,\text{modus}}}{UF_x} \quad (2)$$

and

$$P_{x,\max} = P_{x,\text{modus}} \times UF_x \quad (3)$$

where:

$P_{x,\min}$ = Minimum value of parameter x;
$P_{x,\text{modus}}$ = Most likely value of parameter x;
$P_{x,\max}$ = Maximum value of parameter x;
UF_x = Uncertainty factor applied to parameter x;

[1] When $P_{x,\text{modus}} < 0$, $P_{x,\max}$ and $P_{x,\min}$ change places in the formulas

Table 1: Inventory data of product system "Roof gutter A1"

Process / Commodity	Electricity production	Oil production	Plastic P1 production	Gutter A1 production	Gutter A1 use and demolition	Incineration of P1/A1	Recycling process[c]	Material B production[c,e]	Product system
MJ electricity	1	-1.10^{-2}	-50	-1	0	-1	-25	40	0
kg oil	-6.10^{-3}	1	-0.8	0	0	-0.5	-0.1	0.3	0
kg plastic P1	0	0	1	-325	0	0	0	0	0
100 m produced A1	0	0	0	1	-1	0	0	0	0
100 m installed A1	0	0	0	0	1	0	0	0	0.2[f]
kg incinerated P1/A1	0	0	-0.01[a]	-0.05[a]	-65[a,b]	1	-0.1[a]	0	0
kg A1 in recycling	0	0	0	0	-260[a,b]	0	1	0	0
kg avoided material B	0	0	0	0	0	0	-1.8[a,d]	1	0
kg CO_2	1.10^{-2}	0.5	2	0	0	3	2	-1.5	
kg CH_4	3.10^{-4}	4.10^{-3}	0	0	0	5.10^{-5}	4.10^{-3}	0	
kg N_2O	1.10^{-6}	1.10^{-4}	1.10^{-5}	0	0	5.10^{-5}	3.10^{-4}	-2.10^{-4}	
kg NO_x	3.10^{-4}	2.10^{-3}	5.10^{-2}	0	0	8.10^{-4}	2.10^{-2}	-4.10^{-3}	
kg SO_2	6.10^{-4}	3.10^{-3}	0.1	0	0	2.10^{-4}	1.10^{-2}	-5.10^{-3}	

[a] in addition to economic inflows economic outflows have a negative sign in the technology matrix; [b] the amount of "kg A1 to the recycling process" is computed by multiplying "kg plastic P1" used in the production of 100 m of roof gutter A1 with the "recycling fraction of roof gutter A1". The computation of the amount of waste to the incineration process is done in the same way, but "1 – recycling fraction" is used in the multiplication; [c] the process data of the recycling process and Material B production are only used if the avoided-impacts allocation method is applied; [d] the amount of avoided material B per kg A1 going into the recycling process is computed by multiplying "the amount of A1 going to product system S" with the ratio of the mass of material B1 and the mass of product A1 related to the functional unit of the receiving product system S; [e] the signs of the economic process data and the environmental interventions per kg material B are reversed, because the avoided-impacts allocation method substracts the environmental inventions related to the amount of avoided material B from original product system A1; [f] The fraction of 100 m roof gutter needed to fulfil the functional unit is computed by multiplying "the fraction of 100m of roof gutter, initially applied to a one-family house" with 50 years, divided by the expected lifetime of the roof gutter.

Table 2: Inventory data of product system "Roof gutter A2"

Process / Commodity	Electricity production	Oil production	Plastic P2 production	Gutter A2 production	Gutter A2 use and demolition	Incineration of P2/A2	Recycling process[c]	Material B production[c,e]	Product system
MJ electricity	1	-1.10^{-2}	-40	-2	0	-1	-40	40	0
kg oil	-6.10^{-3}	1	-0.6	0	0	-0.5	-0.5	0.3	0
kg plastic P2	0	0	1	-200	0	0	0	0	0
100 m produced A2	0	0	0	1	-1	0	0	0	0
100 m installed A2	0	0	0	0	1	0	0	0	0.2[f]
kg incinerated P2/A2	0	0	-0.02[a]	-0.05[a]	-20[a,b]	1	-0.2[a]	0	0
kg A2 in recycling	0	0	0	0	-180[a,b]	0	1	0	0
kg avoided material B	0	0	0	0	0	0	-2[a,d]	1	0
kg CO_2	1.10^{-2}	0.5	1.5	0	0	2	2.5	-1.5	
kg CH_4	3.10^{-4}	4.10^{-3}	0	0	0	3.10^{-5}	2.10^{-3}	0	
kg N_2O	1.10^{-6}	1.10^{-4}	3.10^{-4}	0	0	6.10^{-6}	4.10^{-4}	-2.10^{-4}	
kg NO_x	3.10^{-4}	2.10^{-3}	0.5	0	0	6.10^{-4}	3.10^{-2}	-4.10^{-3}	
kg SO_2	6.10^{-4}	3.10^{-3}	1.10^{-2}	0	0	4.10^{-4}	2.10^{-2}	-5.10^{-3}	

[a,b,c,d,e,f] same comments as in **Table 1**

Table 3: Additional input data and uncertainty factors applied to the product systems A1 and A2

Parameters	Product sytem A1	Product system A2	UF[b]
Recycling fraction Ax	0.80	0.90	1.1
Mass of product Ax related to the functional unit of the receiving product system S	250	200	1.1
Mass of material B related to functional unit of the receiving product system S[a]	500	500	1.1
Fraction of 100 m roof gutter, initially applied to a one-family house[a]	0.1	0.1	1.05
Lifetime of roof gutter A1 and A2 (years)[a]	25	25	1.25

[a] it is assumed that these parameters are not product system specific; [b] UF = uncertainty factor

By way of simplification, estimates of the UFs and the applied distribution form are entirely arbitrary. Furthermore, the UFs for the product-specific process data in the two product systems are assumed to be the same, which would not be necessarily true in "real life" cases.

2.2 Global Warming

The Global Warming Potential (GWP) of a gas is "the cumulative radiative forcing between the present and some chosen later time "horizon" caused by a unit mass of gas emitted now, expressed relative to some reference gas" (ALBRITTON et al., 1996). Generally, CO_2 is taken as the reference gas. As a consequence, the uncertainty of the GWP of any trace gas other than CO_2 depends upon the substance-specific uncertainties in the integrated radiative forcing (IF) of the gas itself and on the IF of CO_2 (ALBRITTON et al., 1995, 1996).

A typical uncertainty in the direct IF of various gases, such as N_2O, is estimated to be ± 35%, caused by uncertainties in the parameters "radiative forcing per molecule" and "lifetimes in the atmosphere of the trace gases" (ALBRITTON et al., 1995, 1996). Because a further explanation of the uncertainty distribution is lacking in the IPCC reports, it is assumed in this assessment that the ± 35% uncertainty represents the 95% confidence range of a normal uncertainty distribution (→ *Table 5*). In addition to the direct radiative forcing capacity, the IF of CH_4 depends on indirect contributions to the radiative forcing of CH_4 due to stratospheric ozone and water vapour production. Uncertainty ranges for the IF of CH_4 for the time horizons 20, 100 and 500 years, given by ALBRITTON et al. (1995), are in the same order as the above-mentioned ± 35% uncertainty range. Uncertainties in the IF for CO_2 depend on uncertainties in the carbon cycle. The effect of these uncertainties is not known, because of the large model uncertainties involved (ALBRITTON et al., 1995). As a result, it is impossible to quantify the uncertainties in probabilistic simulation.

Variation in future scenarios of CO_2 and other trace gas emissions also have an effect on GWP-values, although the IF of CO_2 is relatively insensitive to these emission scenarios

Table 4: Uncertainty factors applied to the inventory data of the product systems A1 and A2

Process / Commodity	Electricity production	Oil production	Plastic production	Gutter production	Gutter use and demolition	Incineration of waste	Recycling process	Material B production	Product system
MJ electricity	1.01	1.1	1.05	1.05	1	1.1	1.05	1.1	1
kg oil	1.05	1.01	1.05	1	1	1.1	1.05	1.1	1
kg plastic	1	1	1.01	1.05	1	1	1	1	1
100 m produced gutter	1	1	1	1.01	1	1	1	1	1
100 m installed gutter	1	1	1	1	1	1	1	1	n.a.[a]
kg incinerated waste	1	1	1.2	1.1	n.a.[a]	1.01	1.05	1	1
kg gutter in recycling	1	1	1	1	n.a.[a]	1	1.01	1	1
kg avoided material B	1	1	1	1	1	1	n.a.[a]	1.01	1
kg CO_2	1.1	1.1	1.05	1	1	1.05	1.05	1.05	
kg CH_4	2	2	1	1	1	2	1.1	1	
kg N_2O	5	5	3	1	1	5	3	4	
kg NO_x	1.5	1.5	1.1	1	1	1.5	1.1	1.2	
kg SO_2	1.5	1.5	1.1	1	1	1.5	1.1	1.2	

[a] n.a. = not applicable: uncertainty factors are only applied to input data and not applied to computation outcomes

(CALDEIRA & KASTING, 1993; ALBRITTON et al., 1995). When two very different extreme scenarios are compared with the reference scenario, a maximum difference of ± 15% in GWP-values is found (ALBRITTON et al., 1995). The choice of a reference future atmosphere for a GWP is not a parameter uncertainty, but rather an agreement upon a selection of a future scenario for atmospheric composition, and therefore it causes uncertainty due to choices. This uncertainty is not taken into account in the further assessment here. Nor are other uncertainties and limitations of GWPs quantified. For instance, the GWP concept is not applicable to gases and aerosols that are very unevenly distributed. For this reason, GWPs for sulphur oxides, which probably contribute to negative radiative forcing through aerosol, and NO_x are not estimated by ALBRITTON et al. (1995, 1996).

2.3 Acidification

HEIJUNGS et al. (1992) proposed an "acid equivalents approach" in the computation of the Acidification Factor (AF) of a substance, in which the proton release per kg emission of the substance in the environment is divided by the proton release per kg emission of a reference substance, assuming that emitted substances are fully transformed into protons. Realization of the maximum proton release depends on whether or not the anions which accompany the released protons are completely leached out of the system. The contribution to acidification is reduced when the anions are bound in the soil or removed in biomass (HAUSCHILD & WENZEL, 1998). When SO_2 is taken as the reference substance, the AF of an acidifying substance is caused by the uncertainty in the proton release of SO_2 and the proton release of the substance itself.

For SO_2 emissions the average release of approximately two protons is thought to be representative for terrestrial conditions, because the soil retention of SO_3^{2-} and SO_4^{2-} ions, formed by deposition of SO_2, is considered to be small (FINNVEDEN et al., 1992; HAUSCHILD & WENZEL, 1998). In this assessment a relatively small uncertainty range for average proton release due to SO_2 emissions is considered (→ *Table 5*). For NO_x emissions, the actual proton release is more complicated to derive. The first problem may be that NO and NO_2 emissions are taken together as NO_x which may cause uncertainty in the value of x. NO, however, is measured and

Table 5: Characteristics of the Global Warming Potentials (20, 100 and 500 years time horizon) and Acidification Factors for the emissions considered in this example

	Units	CO_2	CH_4 mean (sd)	N_2O mean (sd)	NO_x [min - max]	SO_2 [min - max]	UD[a]
GWP20	CO_2-eq. (kg)	1	56 (9.8)	280 (49.0)	?	?	normal
GWP100	CO_2-eq. (kg)	1	21 (3.7)	310 (54.3)	?	?	normal
GWP500	CO_2-eq. (kg)	1	6.5 (1.1)	170 (29.8)	?	?	normal
Proton release	-	?	0	0	[0.5 - 0.9]	[1.9 - 2.0]	Uniform

[a] UD = uncertainty distribution

represented as NO_2 in NO_x inventories. Thus, x has a value of 2 which is in line with HAUSCHILD & WENZEL (1998) and HEIJUNGS et al. (1992). Furthermore, it is unclear what average fraction of NO_3^- ions, following from the deposition of nitrogen oxides, is taken up by plants and removed from the system. As a first approximation, the minimum and maximum values for average removal of NO_3^- ions due to harvesting are chosen to be respectively 10% and 50%, resulting in a net release of protons of 50% to 90% of the theoretical maximum (→ *Table 5*).

3 Environmental Profiles

To show the effect on LCA outcomes of uncertainty in the input data, Latin Hypercube simulation is performed with Crystal Ball® (Decisioneering, 1996) in the spreadsheet program Microsoft Excel 7.0® (Microsoft, 1995). This method segments the uncertainty distribution of a parameter into a number of non-overlapping intervals, each having equal probability. In addition, a value from each interval is randomly selected according to the probability distribution within the interval. The randomly selected values from all the parameter uncertainty distributions are inserted in the output equation. Repeated calculations produce a distribution of the predicted output values, reflecting the combined parameter uncertainties. Each model run consisted of 10,000 iterations, which is considered sufficient to obtain a representative frequency chart of the output variables (MORGAN & HENRION, 1990).

The quotients of product system A1 and product system A2 for their potential contribution to global warming and acidification are computed with Equation 4 and used to indicate the significance of differences between the two product systems. When a quotient is significantly lower than 1, product system A1 contributes less to an environmental category than product system A2. When a quotient is significantly higher than 1, the reverse is true. A certain result is considered to be significant if 95% of the iterations lies above or below 1.

$$CI_e = \frac{\sum_{x=1}^{x=n} CF_{e,x} \times E_{A1,x}}{\sum_{x=1}^{x=n} CF_{e,x} \times E_{A2,x}} \quad (4)$$

CI_e = Comparison indicator for environmental category e (dimensionless);
$CF_{e,x}$ = Characterisation factor of substance x in the environmental category e (dimensionless);
$E_{A1,x}$ = Amount of emitted substance x related to product system A1 (kg);
$E_{A2,x}$ = Amount of emitted substance x related to product system A2 (kg);
x = Emission identification number (dimensionless);
n = Number of emission types (dimensionless).

Figures 1 and **2** respectively show the frequency charts of the Global Warming Comparison Indicator with a chosen time horizon of 100 years ($GWCI_{100}$) and the Acidification

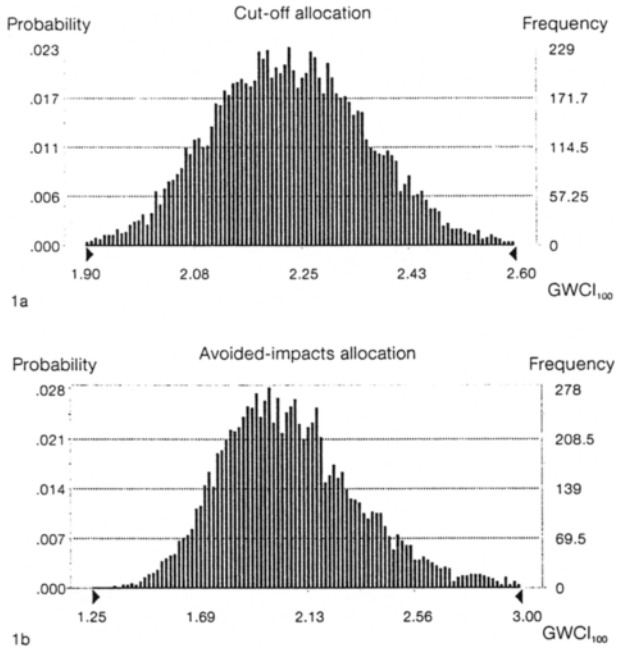

Fig. 1: Frequency charts of the Global Warming Comparison Indicator (time horizon 100 years) after 10,000 model iterations, when using either the cut-off method (1a) or the avoided-impacts method (1b) to allocate environmental burdens associated with the open-loop recycling process

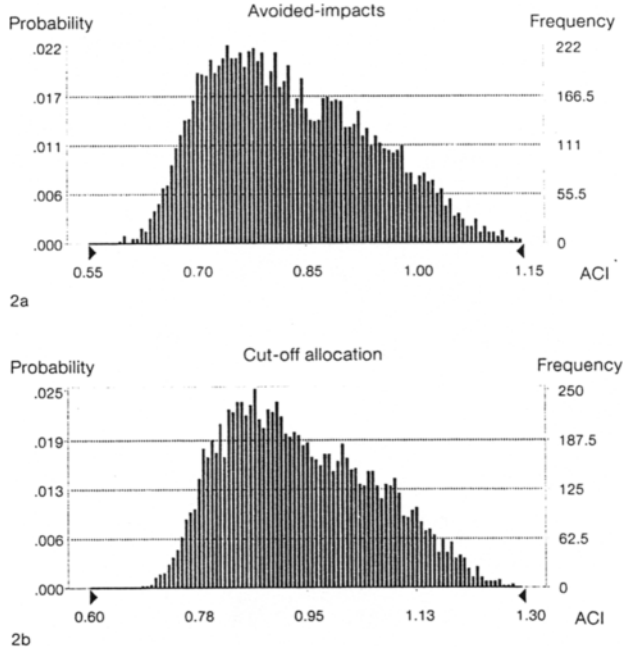

Fig. 2: Frequency charts of the Acidification Comparison Indicator after 10,000 model iterations, when using either the cut-off method (2a) or the avoided-impacts method (2a) to allocate environmental burdens associated with the open-loop recycling process

Table 6: Statistical characteristics of the potential contribution of product systems A1 and A2 respectively to Global Warming (time horizons 20, 100 and 500 years) and Acidification, and the Comparison Indicators for Global Warming (time horizons 20, 100 and 500 years) and Acidification

	Units	Global warming (20y)		Global warming (100y)		Global warming (500y)		Acidification	
		C[a]	A[b]	C[a]	A[b]	C[a]	A[b]	C[a]	A[b]
Product system A1	CO_2/SO_2-eq								
Mean		304.7	212.6	258.4	189.7	236.6	180.1	11.0	9.4
Standard deviation		38.1	30.3	27.9	25.8	24.6	23.5	1.2	1.1
Distribution[c]		LN	LN	LN	LN	LN	LN	LN	LN
Product system A2	CO_2/SO_2-eq								
Mean		137.8	99.8	115.9	91.6	103.1	85.4	11.9	11.5
Standard deviation		17.9	17.6	12.9	15.3	11.0	13.4	2.1	2.2
Distribution[c]		LN	LN	LN	LN	LN	LN	LN	LN
Comparison Indicator	dimensionless								
Mean		2.22	2.13	2.23	2.10	2.30	2.16		
Standard deviation		0.11	0.28	0.12	0.30	0.13	0.32		
Modus								0.85	0.75
Range								[0.7 - 1.25]	[0.6 - 1.15]
Distribution[c]		LN	LN	LN	LN	LN	LN	T	T
Percentage A1 > A2	dimensionless	100%	100%	100%	100%	100%	100%	31.9%	7.8%

[a]C = Cut-off allocation method, [b]A = Avoided-impacts allocation method; [c]LN = Lognormal, T= Triangular

Comparison Indicator (ACI), when using either the cut-off method or the avoided-impacts method to allocate environmental burdens associated with the open-loop recycling process. Table 6 shows some statistical characteristics of the respective comparison indicators. This table also lists the statistics of the potential contribution to global warming and acidification of the two product systems A1 and A2. The results show that the $GWCI_{100}$ lies 100% above 1 regardless of the allocation method used. The same is true for $GWCI_{20}$ and $GWCI_{500}$ (→ *Table 6*). The ACI lies 28.6% and 6.9% above 1, when the cut-off and avoided-impacts allocation method are used, respectively. Thus, product system A2 contributes significantly less to global warming than product system A1; however, when considering the contribution to acidification using the above-mentioned criterion for significance, no significant differences are found between the two product systems.

4 Uncertainty importance analysis

Crystal Ball® is also equipped with a tool which calculates the uncertainty importance of each parameter. This tool calculates the uncertainty importance by computing rank correlation coefficients between every parameter uncertainty and every model outcome, such as the ACI, during the simulation. If a parameter and a model outcome have a high correlation coefficient, this means that the uncertainty in the parameter has a relatively large impact on the uncertainty in the model outcome. In the current assessment, the relative contribution of each parameter uncertainty to the uncertainty of the Comparison Indicators is approximated by the square values of the rank correlation coefficients r normalized to 100%. Table 7 lists the parameters which make a relatively large contribution (> 5%) to the uncertainty of the $GWCI_{100}$ and ACI. In this respect, parameters which dominantly cause uncertainty in the ACI are of most interest, because statistically significant results are not obtained for the ACI as opposed to the GWCIs. Uncertainty in the ACI is almost entirely caused by uncertainty in the proton release due to NO_x emissions, regardless of the allocation method used (→ *Table 7*). Research priority should in this case be given to reducing the uncertainty in the average removal of NO_3^- ions due to harvesting.

If the main goal of the assessment is not to compare products but, for example, to find product improvement options, an uncertainty importance analysis, performed for each product system separately, will be relevant. Tables 8 and 9 show that other parameter uncertainties, such as uncertainty of the lifetime of roof gutters, become important in the separate analyses. The partly changed relevance of parameter uncertainty is explained by the fact that some parameters are not specified per separate product system but are implemented only once in the simulation model. As a consequence, these parameters are mainly "divided out" in the product comparison, while in a separate analysis of the product systems they are not.

Table 7: Uncertainty importance of input parameters, expressed in percentage contribution to the output uncertainty, relevant (> 5%) for determining of the significance of differences between the product systems A1 and A2 for the $GWCI_{100}$ and the ACI

Parameter	Global Warming (100y)		Acidification	
	C[a]	A[b]	C[a]	A[b]
Recycling fraction roof gutter A1 (-)	23.4%	14.7%		
Recycling fraction roof gutter A2 (-)	26.6%	12.6%		
Plastic P1 input in production roof gutter A1 (kg)	14.0%			
Plastic P2 input in production roof gutter A2 (kg)	12.5%			
Mass of product A1 related to the functional unit of the receiving product system S (kg)		13.2%		
Mass of product A2 related to the functional unit of the receiving product system S (kg)		31.3%		
N_2O emission in roof gutter A2 recycling process (kg)	10.8%			
Proton release due to 1 mol NO_x emission (mol)			82.9%	81.0%
NO_x emission in plastic P2 production (kg)			6.7%	6.6%
Total uncertainty importance, explained by above factors	87.3%	71.8%	89.6%	87.6%

[a]C = Cut-off allocation method; [b]A = Avoided-impacts allocation method

Table 8: Uncertainty importance of input parameters, expressed in percentage contribution to the output uncertainty, relevant (> 5%) for determining the contribution to global warming (time horizon 100 years) and acidification of product system A1

Parameter	Global Warming (100y)		Acidification	
	C[a]	A[b]	C[a]	A[b]
Lifetime of roof gutter A1 (years)	73.9%	45.1%	68.2%	66.2%
Recycling fraction roof gutter A1 (-)	5.4%	12.9%		
Mass of product A1 related to the functional unit of the receiving product system S (kg)		11.9%		
Mass of product B related to the functional unit of the receiving product system S (kg)		12.1%		
Fraction of 100 m roof gutter, initially applied to a one-family house (-)	7.7%	5.0%	6.8%	6.7%
Proton release due to 1 mol NO_x emission (mol)			9.1%	11.5%
SO_2 emission per MJ produced electricity (kg)			7.3%	
Total uncertainty importance, explained by above factors	87.0%	87.0%	91.4%	84.4%

[a]C = Cut-off allocation method; [b]A = Avoided-impacts allocation method

Table 9: Uncertainty importance of input parameters, expressed in percentage contribution to the output uncertainty, relevant (> 5%) for determining the contribution to global warming (time horizon 100 years) and acidification of product system A2

Parameter	Global Warming (100y)		Acidification	
	C[a]	A[b]	C[a]	A[b]
Lifetime of roof gutter A2 (years)	69.1%	30.4%	23.0%	21.3%
Recycling fraction roof gutter A2 (-)	6.5%	7.2%		
Mass of product A2 related to the functional unit of the receiving product system S (kg)		19.2%		
Mass of product B related to the functional unit of the receiving product system S (kg)		18.9%		
Fraction of 100 m roof gutter, initially applied to a one-family house (-)	7.1%			
NO_2 emission per kg material B production (kg)		5.5%		
Proton release due to 1 mol NO_x emission (mol)			68.3%	70.3%
Total uncertainty importance, explained by above factors	82.7%	81.2%	91.3%	91.6%

[a]C = Cut-off allocation method; [b]A = Avoided-impacts allocation method

5 Discussion

As shown in this simplified example, the procedure to operationalise uncertainty due to choices and parameter uncertainty in LCAs is relatively straightforward. However, when "real-life" LCAs are analysed, feasibility problems will occur. It will probably not be feasible in LCA case studies to analyse the effect of all possible combinations of choices, to underpin the uncertainty ranges of all the input data used in the inventory, and to perform an extensive parameter uncertainty analysis in the characterisation phase. Options to deal with these problems are discussed below.

When performing LCAs, choices are unavoidable. Aside from the choice how to allocate environmental burdens in open-loop recycling processes, several other choices will lead to uncertainty in LCA outcomes, such as the choice how to allocate environmental burdens in multi-output and multi-waste processes, and the choice of a functional unit. The following procedure, partly based on recommendations in KORTMAN et al. (1996), may help to decrease the number of choice combinations in LCA case studies: (1) formulate several options for every LCA choice; (2) find the two "extreme" options for every choice; (3) construct two "extreme" combinations of options and compute the effect of the two combinations on the LCA outcomes.

Furthermore, in practice it will be very difficult to underpin the uncertainty ranges for the huge number of parameters involved in the inventory analysis. Focusing on key parameter uncertainties will increase the feasibility of the uncertainty analysis and will decrease the validity of the uncertainty analysis only in a limited extent. HEIJUNGS (1996) proposes to first perform a broad sensitivity analysis, using standard uncertainty estimates, to find out what parameters may contribute substantially to the uncertainty in environmental profiles. In a probabilistic simulation program it is possible to perform a sensitivity analysis in the same way as in the uncertainty importance analysis described in the previous section. Each parameter is then characterised with the same percentile sensitivity range and distribution, for example ± 10% of most likely numbers as a uniform distribution. The parameters which together cover 90% of the sensitivity range, for instance, should then get priority to find accurate measurements or better uncertainty estimates. However, a disadvantage of using one standard sensitivity range is that parameters which are initially thought to present a minor contribution to LCA outcomes, but has an expected large unknown uncertainty range, are thrown out of the analysis beforehand. A very rough solution is perhaps found in the use of a number of standard sensitivity ranges for types of environmental interventions, such as the application of several "uncertainty factors" in the roof gutter example used in this article.

A complementary strategy to simplify the uncertainty analysis is to implement uncertainty ranges for accumulated environmental interventions rather than individual parameters in LCA inventories (see KENNEDY et al., 1996). This simplification could be particularly useful in the analysis of the potential importance of background data in the uncertainty analysis. For example, ranges for accumulated emissions per MJ electricity use could be implemented in the sensitivity analysis. If it appears that some of the accumulated emissions may contribute substantially to the uncertainty in model outcomes, a reconstruction of parts of the inventory for electricity production will be necessary. Moreover, a second sensitivity analysis could be performed to find the dominant parameter uncertainties in the computation of the most important accumulated emissions. If potentially dominant parameter uncertainties are found, more sophisticated methods, such as the method described by WEIDEMA & WESNÆS (1996) combined with expert judgement, and measurement of inaccuracies may be used to estimate uncertainty ranges in detail.

In addition to the lack of uncertainty estimates for process data in the inventory analysis, uncertainty pertinent to characterisation factors is generally unknown or very poorly known. An important difference between process data of the inventory and characterisation factors, however, is that process data are directly measured, while characterisation factors are computed with (simplified) environmental models. Therefore, uncertainty ranges for characterisation factors can only be found by a parameter uncertainty analysis within these models. Developers of characterisation factors should pay attention to this aspect, if necessary in co-operation with environmental model experts.

Finally, although operationalising the effect of parameter uncertainties and uncertainty due to choices is important, model uncertainties should not be disregarded. As pointed out in the introduction, model uncertainties, such as the lack of temporal and spatial variability in the assessment, have not been quantified in LCAs (HUIJBREGTS, 1998). Because of these inherent model uncertainties, it is important to avoid the appearance that uncertainty in LCAs is totally quantified with the techniques used in this paper. Other analytical instruments are needed to deal with these model uncertainties.

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